HOW WIDE IS A ROAD? THE ASSOCIATION OF ROADS AND MASS-WASTING IN A FORESTED MONTANE ENVIRONMENT

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ABSTRACT

A spatial data base of 1609 landslides was analysed using a geographic information system to determine landslide frequency in relation to highways. A 126 km long transportation network in a 201 km^2 area of humid-tropical, mountainous, forested terrain in Puerto Rico was used in conjunction with a series of 20 buffer (disturbance) zones varying from 5 to 400 m in length, measured perpendicular to the highways. Average landslide frequency in the study area at distances greater than 85 m from roads was about six landslides per square kilometre. At distances of 85 m or less on either side of a highway, landslide frequency was about 30 landslides per square kilometre. On average, this elevated disturbance rate affected 330 m^2 km^{-2} a^{-1} within the 170 m swath. The mass-wasting rate outside of the disturbance zone affected 40 m^2 km^{-2} a^{-1}. These results indicate that the rate of mass-wasting disturbance is increased from five to eight times in a 170 m wide swath along road corridors. The lateral extent of the environmental impact of roads in the study area is greater than is commonly perceived. The approach described herein demonstrates a simple method to assess the spatial association of mass-wasting with highways. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Mass-wasting has confounded road builders for as long as humans have constructed transportation routes through mountainous terrain. This is particularly true in mountainous humid-tropical settings where frequent high-intensity rainfall often results in widespread mass-wasting. The term ‘mass-wasting’, also referred to here as landsliding, refers to the downward and outward movement of hillslope-forming materials – natural rock, soils, artificial fills or combinations of these materials (Schuster, 1978). Mass-wasting can include falls, topples, slides, spreads and flows. These phenomena are part of the process of hillslope erosion that is responsible for introduction of sediment into streams, rivers, lakes, reservoirs and finally the oceans. When highways are constructed in mountainous environments, the frequency of mass-wasting commonly increases (Varnes, 1978). However, in most settings the actual mass-wasting zone of disturbance associated with highway construction is not well known.

Determination of the mass-wasting zone of disturbance is important for land-use managers and highway engineering who must deal with the costly and sometimes life-threatening problems caused by road-related landslides. Realistic assessment of the impact of proposed highway construction must be quantifiable as road costs may be significantly increased by landsliding during construction (Sowers, 1971). In addition, the environmental impact of new road construction may be greater than anticipated if the effect of landslides associated with highways is only considered immediately proximal to the road. Finally, understanding of forest disturbance regimes is one of the dominant thrusts in modern forest ecology. Improved cognizance of the combined effects of anthropogenic and mass-wasting disturbance may be essential to the characterization of disturbance regimes in montane, landslide-prone environments. It is therefore important to determine: (1) to what degree the presence of roads in mountainous terrain is associated with landslide frequence; and (2) the width of the zone of mass-wasting disturbance identified with highways.

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A 201 km^2 area of Puerto Rico that includes secondary forest and relatively undisturbed forest, known as the Luquillo Experimental Forest (LEF), was selected to address these questions. This study area encompasses the topographic and climatic conditions that typify much of rural Puerto Rico as well as many other humid-tropical regions. The objectives of this study were to determine: (1) if a zone of higher landslide frequency could be recognized adjacent to roads when compared to landslide frequency in areas distant from roads; (2) the width of that disturbance zone; and (3) the rate of mass-wasting disturbance in that zone. This work was accomplished using a digitized spatial data base that included 1609 landslide locations and dimensions mapped from aerial photographs, topography, and a road network from 1:20 000 scale topographic maps (Larsen and Torres-Sánchez, 1996). The data were analysed with vector-based geographic information system (GIS) software, ARC/INFO (ESRI, 1993).

PREVIOUS WORK

The principal causes of anthropogenically induced instability result from increased weight on the hillslope from fill, hillslope oversteepening, removal of slope support in roadcuts, alteration of surface runoff paths, and enhanced runoff rates (Sidle *et al*., 1985). The effect of mass-wasting on roads has been evaluated from the perspective of numerous disciplines. Geomorphologists, engineers, geologists and geographers, among others, have assessed landslide frequency and magnitude in a variety of environments. Fredricksen (1970), Eckhardt (1976), Beschta (1978) and Duncan *et al*. (1987) studied the problem in humid-temperate settings. Much of their work focused on areas where logging was active and mass-wasting had caused extensive damage to access roads. Mass-wasting in these areas degraded fish habitat through the introduction of large amounts of sediment into rivers and streams. Wolfe and Williams (1986) determined that landslide frequency in areas impacted by logging and associated road building was increased by three to 26 times in comparison with nearby undisturbed forested areas. An extensive summary of landslide problems resulting from road building at sites mainly in the Pacific Northwest is included in Sidle *et al*. (1985). They report rates of soil mass movement associated with roads that are as much as 300 times greater than the rates in undisturbed forest.

Studies of road-related mass-wasting in the humid tropics have been limited in part by the level of economic development of most nations in the tropics. The humid tropics have been defined as those areas with consistently high receipt of solar radiation, heat and moisture (Reading *et al*., 1995). Anderson (1983) examined the influence of soil pore-water pressure on road cuts and showed that elevated pore pressure resulting from heavy rainfall caused slope failures along road cuts on the island of St Lucia, West Indies. In addition, he noted that angle and slope plan curvature were significant factors in determing whether a road cut was likely to fail. Maharaj (1993), working in a 15 km^2 watershed in the Port Royal Mountains, Jamaica, documented 866 mostly rainfall-triggered landslides. The greatest frequencies of these landslides were associated with several bedrock types and slopes in excess of 20°. Fifty-four per cent of the landslides were mapped along highways, indicating a strong association of mass-wasting with anthropogenic landscape disturbance.

Haigh *et al*. (1988, 1993) related landslide frequency along Himalayan highways to such factors as the presence or absence of forest, hillslope angle, and rock or soil type. In Thailand, numerous landslides were triggered by a major storm in 1988 in the steeply sloping Khao Luang mountains (DeGraff, 1990). Although road-associated mass-wasting was not discussed by the author, he noted that landslides were larger and most abundant in the anthropogenically perturbed regions of the mountains where rubber was cultivated on steep slopes. Anthropogenic alteration of slopes has resulted in increased frequency of rainfall-induced slope failures in Singapore as well (Chatterjea, 1994). At two urban sites with grass-covered slopes, Chatterjea documented 103 failures after rainstorms. The failures were more abundant and of larger magnitude than in nearby forested areas. Pitts (1992) discusses a variety of slope stability problems that have occurred in Singapore, noting that slopes composed of fill have been the sites of large landslides. He states that lithology is of only marginal importance because of the geotechnical similarities among weathered bedrock types in this humid-tropical setting. The more important factor is structure as shear strengths along structures (i.e. joint planes) are lower than shear strength in the intact material.

Road widening in the Sungei Gombak catchment, Malaysia, resulted in landsliding associated with intense rainfall (Douglas, 1967). Douglas (1968) describes an additional process in the Sungei Gombak catchment,

identical to that observed in parts of the LEF and elsewhere, in which large core stones that have been exposed by accelerated erosion of surrounding soil are destabilized. The core stone may then move, allowing soil and saprolite resting above it to slip downslope, often onto road surfaces. In much of Peninsular Malaysia, landslides are common in deep cuts for road and building excavations, mining and quarry sites, and where housing is constructed on steep terrain (Tan, 1984). Tan notes that infiltration from heavy rains on fill and cut slopes is a particular problem for highway construction in this and other tropical settings.

Another body of literature documents various methods of evaluating landslide hazard through regional mapping and use of a GIS. Brabb (1995) demonstrated the utility of a GIS for assessment of geologic (earthquake, landslide and flood) hazards in San Mateo County, California. This approach included the distribution of landslides in relation to bedrock dip, hillslope angle, soil infiltration and other factors. Also working in San Mateo County, California, Wentworth *et al*. (1987) described a similar approach where several soil engineering characteristics were mapped using a GIS. Wagner *et al*. (1988) used computerized spatial mapping along 400 km of roads in Nepal to evaluate the influence of slope and soil type in relation to landslide occurrence. They demonstrated a strong correlation between landsliding and bedrock type along roads. Hydrologic factors and degree of rock weathering were deemed important as well. Mehrota *et al*. (1991), working in the Himalayas, examined landslide locations in relation to slope, lithology, land use, drainage and structure. These factors were used to derive a numerical weighting from which landslide susceptibility maps were developed. The distribution of mass movements in the Philippines was evaluated by Moore *et al*. (1991). They attributed landslide occurrence to seismic activity and tropical storms and found that deforestation and construction of logging roads dramatically increased the extent and impact of landslides. At a site in Italy, Carrara *et al*. (1991) related the distribution of landslides to land use practices, particularly highway construction and maintenance. Kingsbury *et al*. (1991) used GIS software to evaluate landslide frequency in relation to hillslope angle using triangular irregular network (TIN) modelling to derive 5° slope angle categories for an area near Wellington, New Zealand. The TIN-generated slope characteristics were investigated with a landslide data base derived from aerial photographs. Using landslide frequency, three landslide-hazard classes were determined according to slope: 0–4° (low hazard), 5–15° (moderate hazard), and greater than 15° (high hazard).

In Puerto Rico, Molinelli (1984) documented the association of landsliding with the construction of a major trans-island highway constructed in the 1970s. Landslide problems associated with highway construction in the LEF were studied by Sowers (1971) after construction of a short stretch of mountain-top highway triggered dozens of small slumps and greatly increased the cost and time needed for completion of the road. Scatena and Larsen (1991) and Larsen and Torres-Sánchez (1991) described rainfall-triggered landslides in the LEF triggered by 200–300 mm of precipitation associated with Hurricane Hugo which struck the island in 1989. These landslides were abundant on hillslopes that faced the prevailing wind-driven rain during the storm. The landslides were relatively small and shallow because of the short duration (6 h) of the rainfall. Larsen and Torres-Sánchez (1996) used a GIS to analyse 4000 landslides in a 900 km^2 area of Puerto Rico. They determined that landslides were most abundant on east- and northeast-facing hillslopes that were anthropogenically modified, with gradients greater than 12° and elevations greater than 350 m.

The studies described above provide important insights into landslide frequency and magnitude in a number of mainly tropical environments. The characterization of hillslope angle over a region is common to many of the investigations as a method for evaluating landslide probability. In addition, many of the studies relate high landslide frequency to the alteration of slope and soil stability associated with construction of highways. None of the analyses, however, attempt to determine how far the zone of landslide disturbance extends from roads.

SETTING

Puerto Rico is the smallest island of the Greater Antilles, located about 1700 km southeast of Miami, Florida (Figure 1). The island is in the trade-wind belt at the boundary between the Caribbean Sea and the Atlantic Ocean at 18°N, 66°W. Because of tectonically controlled geologic complexity and strong orographic control on island rainfall distribution, a variety of land-use, topographic and soil characteristics exist in the relatively small (9000 km^2) area of Puerto Rico. Several major bedrock types, typical of island arc systems throughout the

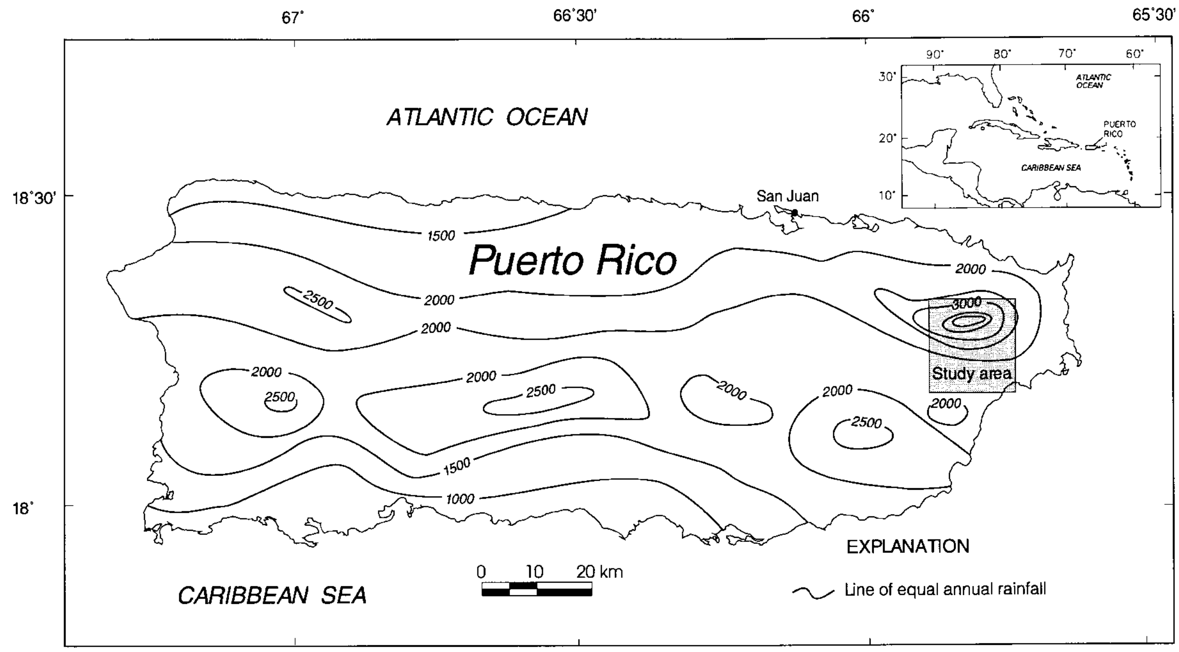

Figure 1. Location of the Luquillo Mountains study area and annual average rainfall isohyets (in mm). Inset shows position of Puerto Rico in the Caribbean basin. Rainfall data from Calvesbert (1970).

world, have been mapped in Puerto Rico (Donnelly, 1989). These are Cretaceous marine-deposited volcaniclastic rock, Tertiary intrusive rock, and Tertiary limestone and sandstone deposits.

The 201 km^2 study area located in eastern Puerto Rico includes most of a 113 km^2 forest preserve, the United States Forest Service-administered LEF (Figure 2). The LEF is an area of relatively undisturbed forested hillslopes and therefore allows for the examination of landslide trends with minimum anthropogenic disturbance beyond the zone of highway construction. Forested areas south of the LEF that were included in the study are in secondary forest. Mean annual rainfall ranges from about 2000 mm to greater than 4000 mm per year, varying with elevation (Calvesbert, 1970). Much of the annual precipitation occurs in medium- to high-intensity showers associated with easterly waves and tropical disturbances. Elevation in the LEF ranges from mean sea level to 1034 m. Topography is moderately steep to rugged and mountain slopes are deeply dissected with perennial and ephemeral streams.

Gradual forest removal in Puerto Rico, including areas surrounding what is now the LEF, began in the 1600s as land was cleared for agriculture by European settlers. After three centuries of extensive agricultural land use, most (94 per cent) of Puerto Rico's 890 000 ha of land had been deforested by the late 1940s (Birdsey and Weaver, 1987). The term 'deforestation' defines anthropogenic changes to pristine forest that include not only clear cutting, but also less disturbing actions such as selective timber harvesting and charcoal burning. Charcoal production was a major industry in the Luquillo Mountains during the 1940s (García-Montiel and Scatena, 1994). A shift to industry began in the 1950s and has resulted in much abandoned pasture and farmland recovering to forest. By 1985, forest area had increased to about 34 per cent of the total land area of the island (Birdsey and Weaver, 1987).

METHODS

The study area was examined using vector-based GIS software and a digitized data base that included topography, land-use classification, a transportation network, and the locations and dimensions of 1609 landslides. The landslide data base used was derived from previous United States Geological Survey work in

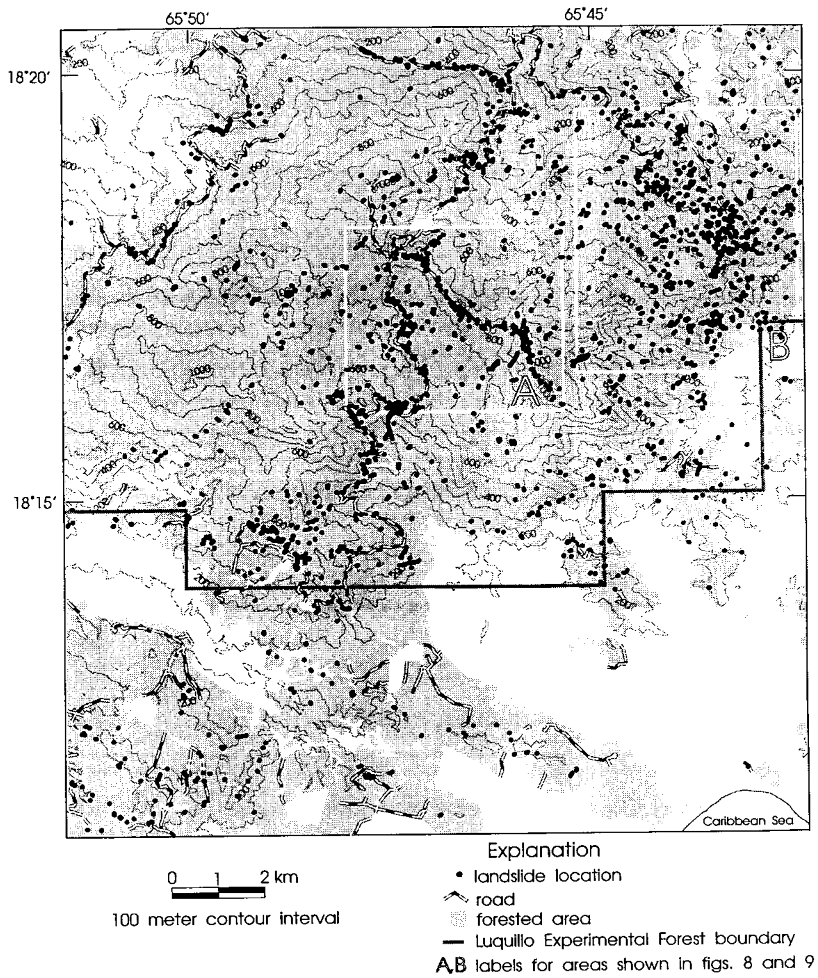

Figure 2. Landslide locations, simplified highway network, forested area, and generalized topography in the Luquillo Mountains, Puerto Rico. Highways are not shown outside of forested or sloping areas.

which landslide locations were digitized from four sets of 1:20 000 scale stereoscopic aerial photographs dating from 1951 to 1990 (Larsen and Torres-Sánchez, 1996). The aerial photographs used in this study cover a period of 40 years and landslides as old as 10 years were visible before revegetation masked most scars. This indicates that aerial photographs record about a 50 year period of landslide activity. For the present study, the land-use classification was used to eliminate all non-forested areas from the analysis. This was done to isolate road-building disturbance from other anthropogenic disturbance such as farming and grazing. No roads or landslides outside of the forested areas were included in the analysis. The remaining 201 km^2 forested area was extracted from the larger 275km^2 rectangle shown in Figure 2.

Landslide lengths and widths were estimated from aerial photographs (Larsen and Torres-Sánchez, 1966). Additionally, based on their morphology, landslides were categorized as debris flows, shallow soil slips, slumps, and debris avalanches. Approximate depths were assigned based on the landslide category and field checking. Field checking of recent landslide scar locations indicates that positional precision determined from the photographs is ±5 m. Using 1:20 000 scale topographic maps, lengths from roads to the end of a hillslope were determined for 132 cases by measuring the map distance from a road segment to the nearest fluve or interfluve whose slope was perpendicular to the road axis. The 132 cases were selected at approximately 1 km, spacing along the 126 km road network.

Table I. Results of GIS analysis of 1609 landslide locations in 20 buffer zones along highways in forested areas of the Luquillo Mountains, Puerto Rico. The location of the proximal, middle or distal end of the scar (with respect to roads) determined to which buffer the scar was assigned. Note that some computations may appear incorrect due to rounding

Buffer width (m)	Buffer area (km^2)	Cumulative area (km^2)	No. of landslides: Proximal	No. of landslides: Distal buffer	No. of landslides: Middle	Landslides per km^2: Proximal	Landslides per km^2: Distal buffer	Landslides per km^2: Middle	Landslide area (ha): Proximal	Landslide area (ha): Distal buffer	Landslide area (ha per km^2 of buffer): Proximal	Landslide area (ha per km^2 of buffer): Distal buffer
5	1·2	1·2	175	1	2	144	1	2	13·6	0·1	11·2	0·0
10	1·0	2·2	78	7	25	81	7	26	4·7	0·1	4·8	0·1
15	0·9	3·1	34	19	64	36	20	69	2·1	0·3	2·2	0·3
20	0·9	4·1	29	37	63	31	39	67	0·9	0·7	0·9	0·8
25	0·9	5·0	20	38	47	22	42	52	1·0	1·6	1·1	1·8
30	0·9	5·9	17	37	46	19	41	51	0·6	1·7	0·7	1·9
35	0·9	6·7	9	39	32	10	44	36	0·4	1·4	0·5	1·6
40	0·9	7·6	7	38	27	8	44	31	0·2	1·8	0·3	2·1
50	1·8	9·4	19	56	33	11	31	18	0·4	3·1	0·2	1·8
60	1·8	11·2	22	41	31	12	23	17	0·6	2·1	0·3	1·2
70	1·8	13·0	24	42	20	13	23	11	2·6	1·6	1·5	0·9
85	2·5	15·5	27	50	40	11	20	16	1·4	3·2	0·5	1·3
100	2·5	18·0	30	28	16	12	11	6	1·6	1·3	0·6	0·5
125	4·4	22·5	44	58	56	10	13	13	1·3	1·7	0·3	0·4
150	4·4	26·8	47	47	44	11	11	10	2·3	3·7	0·5	0·8
200	7·2	34·0	64	79	76	9	11	11	1·9	5·2	0·3	0·7
250	7·4	41·4	69	65	64	9	9	9	1·9	1·4	0·3	0·2
300	7·9	49·3	79	73	73	10	9	9	1·9	3·1	0·2	0·4
350	7·3	56·6	55	66	66	8	9	9	2·1	2·2	0·3	0·3
400	7·7	64·3	68	66	66	9	9	9	1·7	5·1	0·2	0·7

The complete transportation network included 670 km of roads, foot trails and four-wheel drive tracks. This network was simplified using GIS software to eliminate all foot trails as their effect on hillslope instability was considered insignificant, at least for features recognizable in 1:20 000 scale aerial photographs. In addition, all roads in areas of zero or near-zero slope were eliminated. This was possible as the landslides included in this study were rare on slopes of less than 4°, predominantly shallow (1–2 m deep), small (median surface area of 180 m^2), and rainfall-triggered (Larsen and Simon, 1993; Larsen and Torres-Sánchez, 1996). Finally, all roads in non-forested areas were eliminated. The resulting transportation network totalled 126 km in length (Figure 2). These remaining highways are narrow, two-lane, asphalt-paved roads 6–7 m wide with gravel or soil shoulders of 1–2 m on each side.

The next step was the creation of disturbance zones, here referred to using the GIS term 'buffer' zone, along highways using GIS software. The buffer lengths used in this analysis were 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 85, 100, 125, 150, 200, 250, 300, 350, and 400 m, measured perpendicular to the highway axis. These lengths were measured on both sides of roads and represent a zone that is twice as wide as the value listed above – a 100 m buffer length therefore describes a zone or swath 200 m wide along the road. Some length distortion occurs using this approach in as much as lengths are map distances and do not account for the effects of hillslope angle.

The number of landslides that were located in the various buffer zones was then determined by digitally overlaying the landslide location coverage with the buffer coverage. Landslide scars were assigned to a buffer zone using three approaches: (1) the zone in which the proximal end of the scar, with respect to a road, was located; (2) the zone in which the distal end of the scar, with respect to a road, was located; and (3) the midpoint of the buffer zones spanned by the scar. This technique attributes a landslide to a particular buffer zone even if only part of that landslide is actually within that zone. Landslide scars crossed a road in six instances. However, the proximal and distal ends and midpoints were assigned in the same manner. Finally, GIS software was used to determine the total area of each buffer zone and the sum of all landslide scar areas and volumes in each buffer zone.

RESULTS

The buffer analysis described above allows discrimination of approximate landslide frequency in 20 zones of increasing length measured perpendicular to the highway network (Table I). By calculating the number of

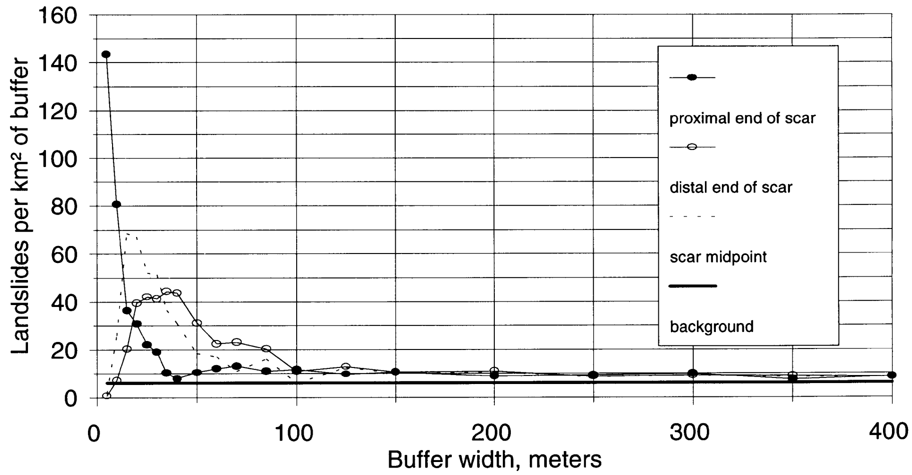

Figure 3. Landslide scars per square kilometre with midpoint, proximal and distal ends within each buffer zone extending 5 to 400 m from roads in forested areas of the Luquillo Mountains, Puerto Rico. Background rate is for those scars not encountered within 85 m of highways.

Table II. Mass-wasting in forested areas within and beyond 85 m of roads in the Luquillo Mountains, Puerto Rico. Landslide surface areas and depths measured from 1:20 000 scale aerial photographs representing a 50 year time span. Volumes estimated by multiplying surface area by depth of scar. Mass estimated by multiplying landslide volume by average regolith density of 1300 kg m^{-3}. Note that some computations may appear to be incorrect due to rounding

	Beyond 85 m	Within 85 m
Number of landslides	1148	461
Study area (km^2)	186	15
Landslides per km^2	6	30
Landslide surface area (m^2)	385 000	252 000
Landslide surface area (m^2 km^{-2})	2100	16 300
Landslide surface area (m^2 km^{-2} a^{-1})	40	330
Landslide volume (m^3 km^{-2} a^{-1})	100	700
Mass-wasting (Mg km^{-2} a^{-1})	200	1000

landslides per square kilometre in each buffer zone, landslide frequency is normalized to the surface area represented by each buffer zone and provides an estimate of spatial landslide frequency in relation to the highways. The total of 1609 landslides distributed over the entire 201 km^2 study area represents an average frequency of about eight landslides per square kilometre. Landslide frequency is greatest within about 40 m of roads and is relatively high as far as 85 m from roads (Figure 3). If only those scars are counted whose proximal end or midpoint is within buffers of 85 m or less, landslide frequency is 30 per square kilometre (Table II). For landslide scars whose entirety is located at 85 m and beyond, landslide frequency averages six per square kilometre. Landslide frequency in areas beyond 400 m of roads averages five per square kilometre and for areas between 85 and 400 m of roads the average is nine per square kilometre. The average of six per square kilometre is used here as a background rate, representing conditions in relatively undisturbed forest (Figure 3). Landslide frequency within 85 m of roads is therefore five times higher than in undisturbed forest.

A plot of total landslide scar surface area versus buffer length also shows a gradational decline with buffer length. This is shown as the landslide scar surface areas normalized by dividing by square kilometres of buffer area (Figure 4). Within 85 m of roads, landslide scars amount to about 16 300 m^2 km^{-2} and beyond 85 m the surface area of landslide scars is 2100 m^2 km^{-2} (Table II). This is an eight-fold difference in surface area affected by mass-wasting.

As buffer lengths are increased, large portions of the study area are included. For example, at 100 m length, about 18 km^2 of the study area is encompassed (Table I). The cumulative number of landslides overlapping the

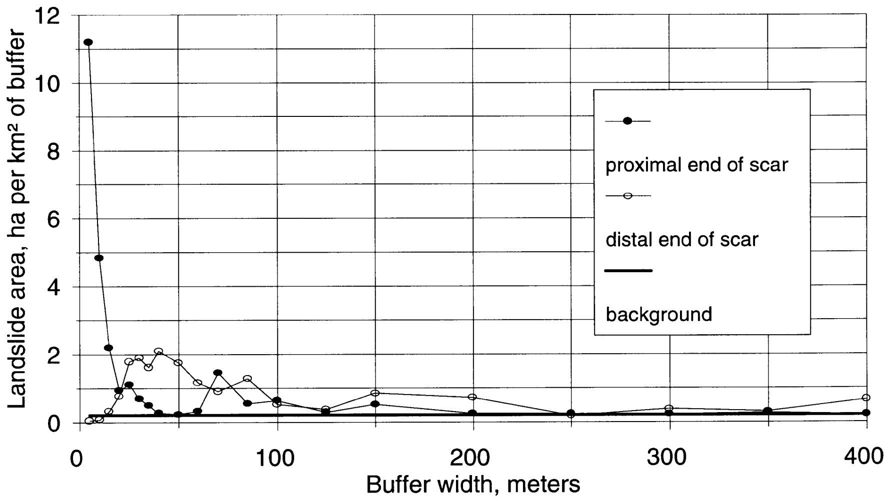

Figure 4. Landslide scar surface area (hectares per square kilometre) for distal and proximal ends of scars (with respect to roads) within buffer zones extending 5 to 400 m from roads in forested areas of the Luquillo Mountains, Puerto Rico. Background rate is for those scars not encountered within 85 m of highways.

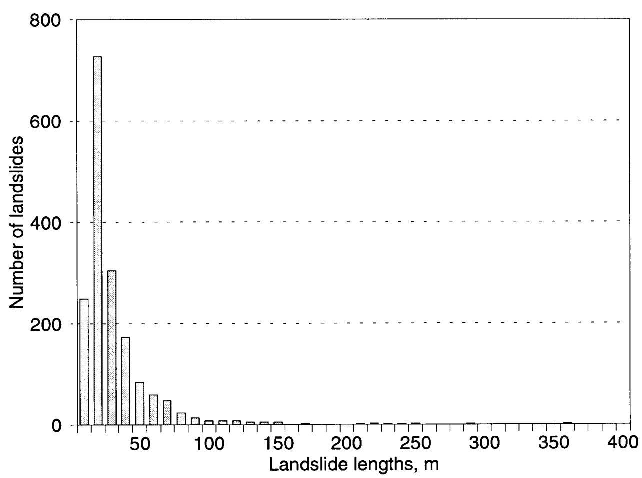

Figure 5. Frequency of landslide scar lengths in the Luquillo Mountains, Puerto Rico. Mean length is 30 m, median is 20 m, and n=1479.

buffer zones increases as buffer length is expanded: at 20 m buffer length, the proximal end of 316 of the landslide scars is accounted for, and at 85 m buffer length, 461, or more than one-quarter of the 1609 landslides, are included. On average, a landslide scar is encountered about every 440 m along roads within the 15 m buffer zone. This is approximately the distance at which a landslide scar would be visible to the casual observer in this forested setting.

Landslide scar lengths were relatively uniform, with a median of 20 m, mean of 30 m and standard deviation of 30 m (Figure 5). Most landslides in the study area are shallow soil slips and slumps (Larsen and Torres-Sánchez, 1996) which, unlike debris flows and debris avalanches, have relatively short downslope lengths. The median distance measured between roads and nearest fluves or interfluves was 400 m (Figure 6). These distances had a standard deviation of 440 m.

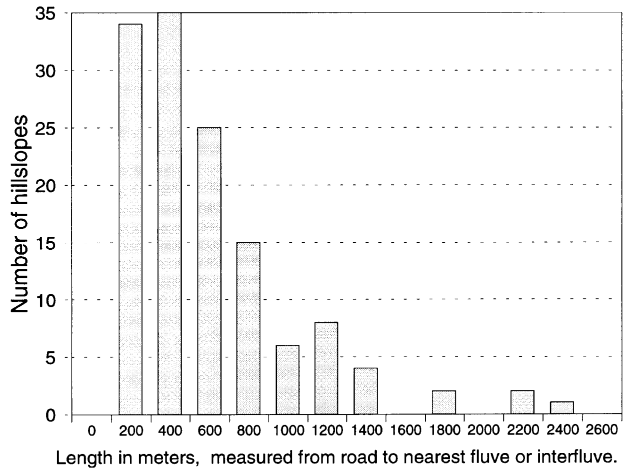

Figure 6. Frequency of hillslope lengths from roads in the Luquillo Mountains, Puerto Rico. Mean length is 510 m, median is 400 m, and *n*=132.

DISCUSSION

Landslide scars were abundant throughout the highest elevation, wettest parts of the study area where hillslopes are steep (Figure 2). In the southern part of the study area there are far fewer scars visible. This latter region has lower mean annual rainfall and gentler slopes than the high-elevation area. A number of factors, such as hillslope gradient and bedrock dip angle, are known to affect hillslope stability. The highway disturbance zone analysis described here indicates that even if these important factors are not considered, a strong association between roads and landslide frequency can be demonstrated. For the Luquillo Mountains, landslide disturbance is associated with roads at distances of as much as 85 m from where they are constructed. Beyond this distance, no association is apparent. Roadside landsliding may seem like a minor disturbance if only those scars immediately adjacent to the highway are considered. However, the 85 m buffer length, or 170 m swath through the Luquillo Mountains, represents a sizeable area of the land surface (Figure 7).

The use of a GIS reveals the spatial association of mass-wasting within 85 m of highways and provides a possible explanation for the mechanism by which it occurs. The low landslide frequency beyond the 85 m buffer, at first consideration, might appear to be simply a function of the length from roads to fluves or interfluves. However, this can probably be discounted as a sample of 132 hillslope lengths indicates that the median distance from a road to the nearest fluve or interfluve is 400 m (Figure 6). Alternatively, the frequency distribution of landslide lengths indicates that scar length may partially explain the extent of the 85 m buffer (disturbance) zone, as the median landslide length is 20 m with a 30 m standard deviation (Figure 5). Larsen and Simon (1993) demonstrated that 200 mm of rainfall accumulation over a period of one to several days was a minimal threshold for landsliding in the central mountains of Puerto Rico. Storms of this magnitude have a recurrence interval of 1 to 5 years (Miller, 1965; US Department of Commerce, 1961). As much of the highway network in the Luquillo Mountains was constructed in the 1930s, storms capable of triggering at least some landslides have occurred relatively frequently since the roads were built. The initial road building causes a number of landslides and tends to destabilize hillslopes above and below roads (Sowers, 1971). The initial landslide scars should propagate both up- and downslope until the entire distance from road to ridge or valley bottom has reached an equilibrium. Because landslide headscarps are oversteepened and therefore unstable, subsequent storms may trigger additional failure at headscarps causing the scarp to migrate upslope over time until it reaches a ridge top. In addition, because many scars are formed by shallow soil slips, they do not have sufficient mass and velocity to propagate all the way downslope to a stream channel during the initial failure (Larsen and Torres-Sánchez, 1996). Each recurrent failure, however, has the potential to lengthen the landslide track downslope because of the additional debris that is dislodged from the headscarp.

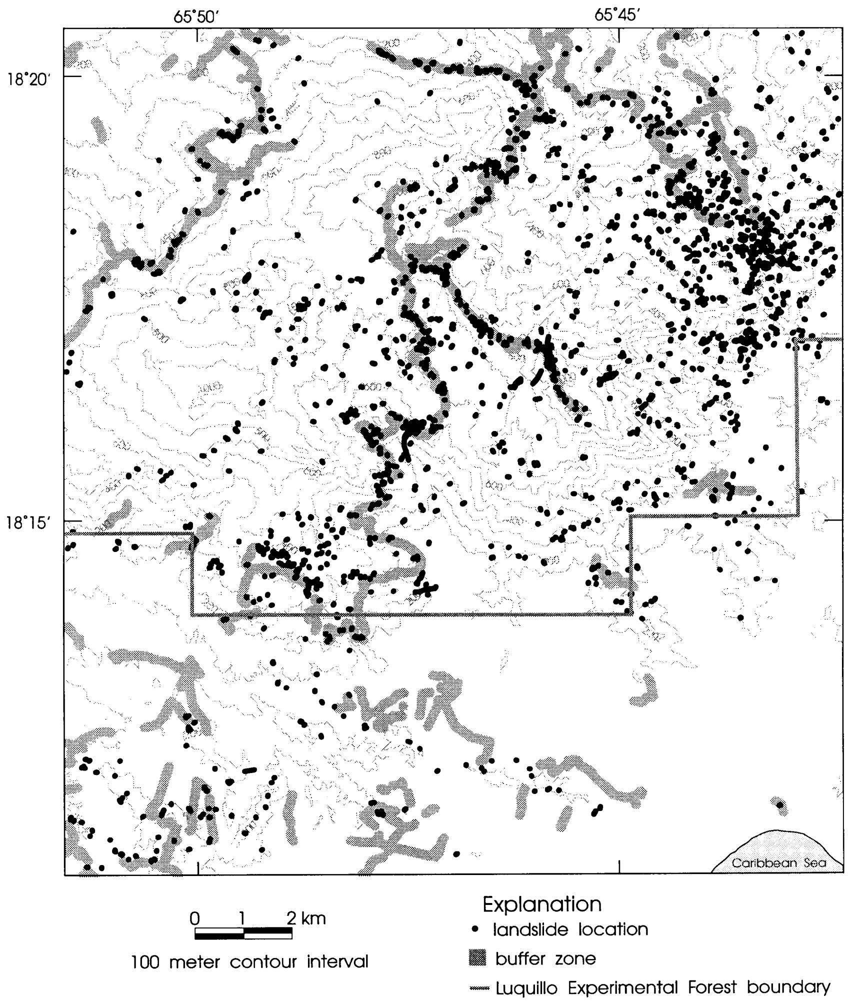

Figure 7. Landslide locations in 85 m wide buffer zone (170 m swath) along simplified highway network, and generalized topography in the Luquillo Mountains, Puerto Rico.

While rigorous investigation of this landslide scar propogation hypothesis was beyond the scope of this study, the landslide frequency data indicate that the hypothesis is plausible. The highest landslide frequency is noted within about 40 m of roads (Figure 3), a distance comparable to the 20 m median landslide scar length, especially considering that the precision of measurements is no better than 5 m. The 85 m zone of high landslide disturbance may represent an intermediate stage in hillslope adjustment to mass-wasting intensified by 20th century road building.

Landscape disturbance and soil erosion

The 85 m zone of high mass-wasting disturbance encompasses an area of 15 km^2 or 8 per cent of the total study area. Using the 50 year temporal estimate of landslide frequency in combination with landslide surface area, an approximate disturbance rate in the 85 m buffer zone can be estimated (Table II). The temporal rate of 30 landslides per square kilometre attributed to the 15 km^2 buffer zone represents a minimum of about 60 landslides per square kilometre per century in that zone. Summing landslide surface area, soil erosion affects at least 330 m^2 km^{-2} a^{-1} (Table II). The estimated mass of soil and regolith eroded within the 85 m disturbance zone is 1000 Mg km^{-2} a^{-1} calculated by multiplying landslide volumes by an average soil and regolith density of 1300 kg m^{-3} (Larsen and Torres-Sánchez, 1996). The high rate of mass-wasting erosion in the 85 m disturbance zone means that the sediment loads in nearby fluvial systems are episodically affected by this landslide

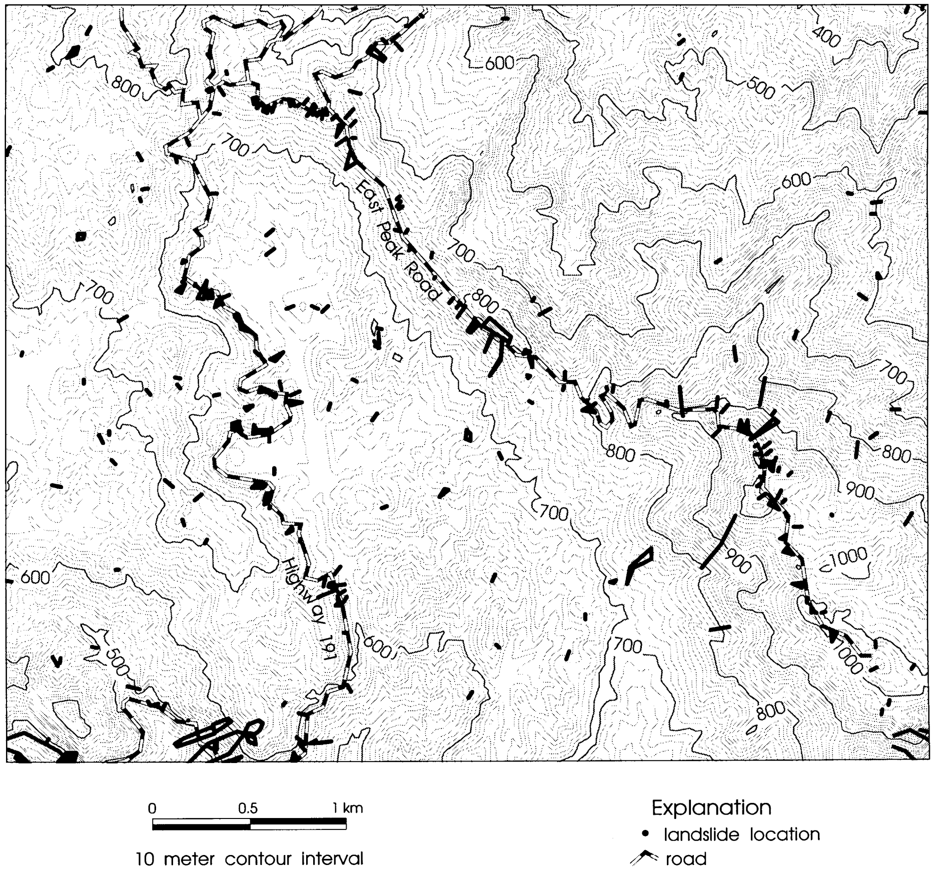

Figure 8. Landslide locations in the vicinity of the East Peak Road and Highway 191 in the Luquillo Mountains, Puerto Rico. See Figure 2, box A, for location.

disturbance. However, annual suspended sediment yield from several rivers draining the Luquillo Mountains ranges from 100 to 400 Mg km^{-2} a^{-1}, indicating that most of the eroded colluvium is in storage (McDowell and Asbury, 1994; Larsen *et al*., 1995).

East Peak Road and Highway 191

An example of road-associated failures that resulted in significant cost increases and delays in project completion is shown in Figure 8. A total of 83 landslide scars are visible along the 6 km long East Peak Road. Many of the landslides occurred during the construction of the road between 1960 and 1963. The landslides, mainly slumps and shallow soil slips which were documented both in cuts and fills, plagued construction and delayed project completion by 2 years beyond the planned 8 month construction period (Sowers, 1971). Additionally, the cost of the road was more than doubled and a complete redesign of the project was necessary.

Located just west of the East Peak Road, a 7 km stretch of Highway 191 (Figure 8) has been closed since 1970 because of several large debris avalanche scars that cut the road after a 5 day rainfall of more than 800 mm (Larsen and Simon, 1993). In addition, more than 60 shallow soil slips, slumps and debris flows along the highway have contributed to the difficulties confronting managing authorities in attempts to re-open the road.

Hurricane Hugo landsliding

It is important to note that mass-wasting disturbance in the Luquillo Mountains is not solely associated with road building and maintenance. Although landslide activity attributed to road construction is most visible and often the most damaging to infrastructure, numerous rainfall-triggered landslides associated with a tropical

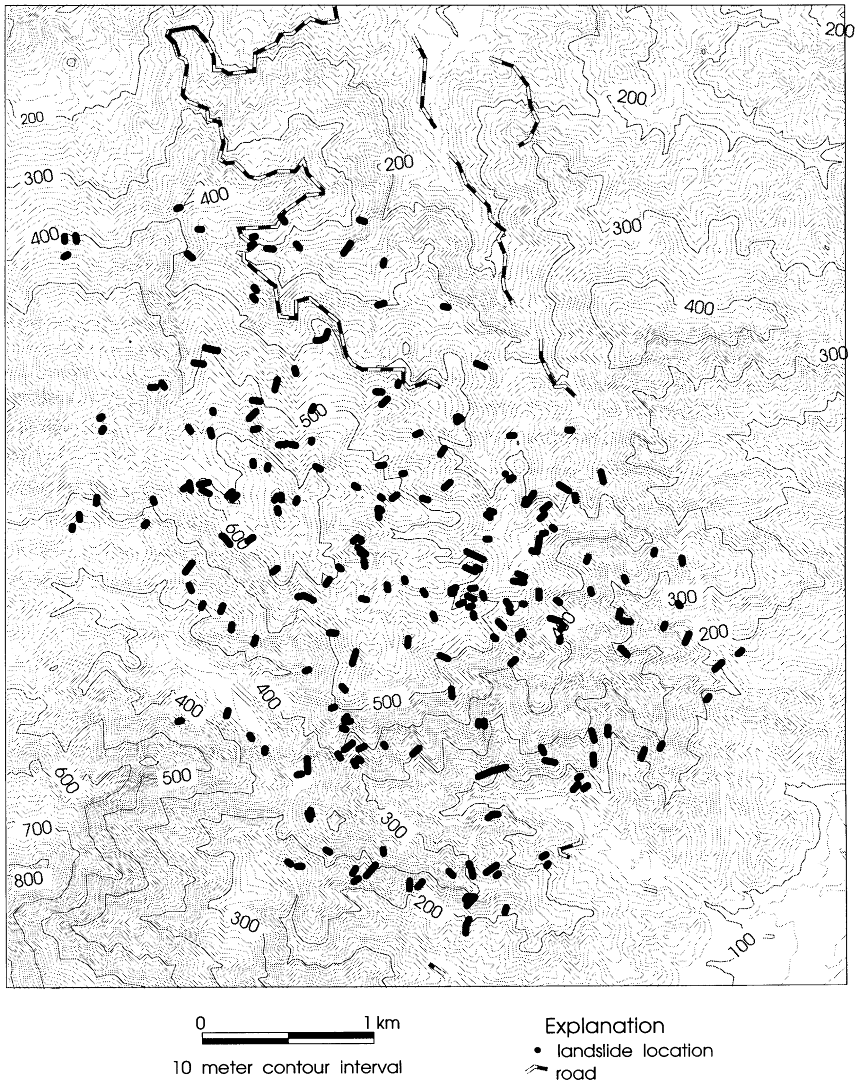

Figure 9. Area of the eastern Luquillo Mountains showing 219 landslides associated with rainfall from the 1989 hurricane in the Luquillo Mountains, Puerto Rico. See Figure 2, box B, for location.

disturbance have been observed in relatively undisturbed forest (Figure 9). Because only one hurricane is well documented by aerial photograph sets in the LEF, it is difficult to determine if Hurricane Hugo landslide frequency and distribution typify the effects of hurricane rainfall. Nevertheless, it provides an example of the impact of a single high-magnitude storm.

In 1989, Hurricane Hugo crossed the northeastern part of Puerto Rico and brought 200–300 mm of rain in a 24 hour period; most of this rainfall was recorded in 6 h (Scatena and Larsen, 1991; Larsen and Torres-Sánchez, 1992). More than 400 landslides triggered by the hurricane were mapped in the Luquillo Mountains. These were mainly shallow soil slips and debris flows that occurred on north-facing hillslopes where rainfall accumulation and windspeed were greatest. A total of 219 landslides triggered by Hurricane Hugo were mapped in the area that was closest to the hurricane eye (Figure 9). This area has a high landslide frequency relative to other areas of the LEF, although the concentration of landslide scars mapped in this area is at least partially the result of using a 1990 set of photographs which optimized scar visibility. Note that the rectilinear area of landslide distribution is an artifact of the area of available aerial photographic coverage. Less than 2 per cent of the

landslide scars shown are within 85 m of the roads in this area, indicating that intense storm rainfall can trigger abundant landslides regardless of the presence or absence of highways.

CONCLUSIONS

The results of these analyses indicate that the zone of mass-wasting disturbance associated with highway construction is extensive. Landslide frequency was high within 85 m of highways. In this 170 m wide zone, the frequency of 30 landslides per square kilometre was five times higher than the study area background frequency of about six landslides per square kilometre. This disturbance zone represents 8 per cent of the study area and indicates that extensive areas are affected by mass-wasting when highways are constructed and maintained in the Luquillo Mountains. For every kilometre of highway length, approximately 12 ha of the 201 km^2 study area has greatly increased landslide frequency.

The frequent road maintenance required in landslide-prone regions places many roadside hillslopes in a state of dynamic instability. Each time a rainstorm triggers soil slips, slumps and other types of failures along the right-of-way, road crews clear the debris, often dumping it on the downslope side of the highway. Presumably, the principal causes of hillslope instability in the 85 m zone are increased weight on the hillslope from these debris and infill deposits, hillslope oversteepening, removal of slope support in cuts, and alteration of surface runoff paths including increased depth and rates of runoff. These causes of instability are likely to propagate up- and downslope from roads.

These results indicate that the quantification of landslide frequency, magnitude and distribution in mountainous terrain is an important consideration in calculating the cost of new highway construction and the maintenance of existing highways. In addition, the environmental impact of highways may be greater than commonly perceived because of the apparent association of high landslide frequency as far as 85 m away from existing roads in the study area. Forest ecologists interested in disturbance regimes in the Luquillo Mountains, and possibly elsewhere in similar environments, may want to consider zones within 85 m of existing or abandoned highways as too anthropogenically disturbed to include in models of natural disturbance. Nonetheless, landslides are abundant in relatively undisturbed forested areas when large-magnitude storms such as hurricanes occur.

This study demonstrates a relatively simple means of determining the extent of road-associated landslide activity in a region, once a topographic, transportation and landslide location data base has been developed. Finally, the question raised in the title should be answered: in the forested area of the Luquillo Mountains, a road is 170 m wide, or several multiples of median landslide length on either side of road corridors.

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REFERENCES

Anderson, M. G. 1983. 'Road-cut slope topography and stability relationships in St. Lucia, West Indies', *Applied Geography,* **3**, 104–114.

Beschta, R. L. 1978. 'Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range', *Water Resources Research,* **14**, 1011–1016.

Birdsey, R. A. and Weaver, P. L. 1987. *Forest Area Trends in Puerto Rico,* US Department of Agriculture, Forest Service Research Note **SO-331**, 5 pp.

Brabb, E. E. 1995. 'The San Mateo County, California GIS project for predicting the consequences of hazardous geologic processes', in Carrara, A. and Guzzeti, F. (Eds), *Geographical Information Systems in Assessing Natural Hazards,* Kluwer Academic Publishers, Dordrecht, 299–334.

Calvesbert, R. J. 1970. *Climate of Puerto Rico and the US Virgin Islands,* US Department of Commerce, Climatography of the States **60–52**, 29 pp.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V. and Reichenbach, P. 1991. 'GIS techniques and statistical models in evaluating landslide hazard', *Earth Surface Processes and Landforms,* **16**, 427–445.

Chatterjea, K. 1994. 'Dynamics of fluvial and slope processes in the changing geomorphic environment of Singapore', *Earth Surface Processes and Landforms*, **19**, 585–607.

DeGraff, J. V. 1990. 'Landslide dams from the November 1988 storm event in southern Thailand', *Landslide News, Japan Landslide Society, Tokyo*, **4**, 12–15.

Donnelly, T. W. 1989. 'Geologic history of the Caribbean and Central America', in Bally, A. W. and Palemer, A. R. (Eds), *The Geology of North America – An Overview*, Geological Society of America, The Geology of North America, **A**, 299–321.

Douglas, I. 1967. *Natural and man made erosion in the humid tropics of Australia, Malaysia, and Singapore,* International Association of Scientific Hydrology, **75**, 17–30.

Douglas, I. 1968. 'Erosion in the Sungei Gombak catchment Selangor', *Journal of Tropical Geography*, **26**, 1–16.

Duncan, S. H., Ward, J. W. and Anderson, R. J. 1987. 'A method for assessing landslide potential as an aid in forest road placement', *Northwest Science*, **61**(3), 152–159.

Eckhardt, D. A. V. 1976. *Sediment discharge from an area of highway construction, Applemans Run basin, Columbia County, Pennsylvania*, US Geological Survey, Water-Resources Investigation Report **76–111**, 25 pp.

ESRI, 1993. *Understanding GIS – The ARC/INFO Method*, John Wiley & Sons, New York, 535 pp.

Fredricksen, R. L. 1970. *Erosion and sedimentation following road construction and timber harvest on unstable soils in three small Oregon watersheds*, US Forest Service Research Paper **PNW–104**, 15 pp.

García-Montiel, D. C. and Scatena, F. N. 1994. 'The effect of human activity on the structure and composition of a tropical forest, Puerto Rico', *Forest Ecology and Management*, **63**, 57–78.

Haigh, M. J., Rawat, J. S. and Bartarya, S. K. 1988. 'Environmental correlations of landslide frequency along new highways in the Himalaya – preliminary results', *Catena*, **15**, 539–553.

Haigh, M. J., Rawat, J. S., Bartarya, S. K. and Rawat, M. S. 1993. 'Factors affecting landslide morphology along new highways in the Central Himalaya', *Transactions, Japanese Geomorphological Union*, **14**, 99–123.

Kingsbury, P. A., Hastie, W. J. and Harrington, A. J. 1991. 'Regional landslip hazard assessment using a geographic information system', in Bell, D. H. (Ed.), *Landslides, Proceedings of the Sixth International Symposium,* Christchurch, New Zealand, 995–999.

Larsen, M. C. and Simon, A. 1993. 'Rainfall-threshold conditions for landslides in a humid-tropical system, Puerto Rico', *Geografiska Annaler*, **75A**(1–2), 13–23.

Larsen, M. C. and Torres-Sánchez, A. J. 1992. 'Landslides triggered by Hurricane Hugo in eastern Puerto Rico, September 1989', *Caribbean Journal of Science*, **28**(3–4), 113–125.

Larsen, M. C. and Torres Sánchez, A. J. 1996. *Geographic relations of landslide distribution and assessment of landslide hazards in the Blanco, Cibuco, and Coamo river basins, Puerto Rico,* US Geological Survey, Water Resources Investigations Report **95–4029**, 56 pp.

Larsen, M. C., Huntington, T. G., Booker, D. L., Concepción, I. M., Parks, J. E., Pojunas, T. P. and Torres-Sánchez, A. J. 1995. 'Suspended sediment transport in small upland humid watersheds undergoing afforestation following human disturbance: a comparison of tropical and temperate environments' (abstract), EOS, *Transactions American Geophysical Union*, **76**(46), F260.

Maharaj, R. J. 1993. 'Landslide processes and landslide susceptibility analysis from an upland watershed – a case study from St. Andrew, Jamaica, West Indies', *Engineering Geology*, **34**, 53–79.

McDowell, W. H. and Asbury, C. E. 1994. 'Export of carbon, nitrogen, and suspended sediment from three tropical montane watersheds', *Limnology and Oceanography*, **39**(1), 111–125.

Mehrotra, G. S., Sarkar, S. and Dharmaraju, R. 1991. 'Landslide hazard assessment in Rishikesh-Tehri area, Garhwal Himalaya', in Bell, D. H. (Ed.), *Landslides, Proceedings of the Sixth International Symposium,* Christchurch, New Zealand, 1001–1007.

Miller, J. F. 1965. *Two- to ten-day rainfall for return periods of 2 to 100 years in Puerto Rico and Virgin Islands,* Weather Bureau, US Department of Commerce, Technical Paper **53**, 35 pp.

Molinelli, J. A. 1984. *Geomorphic processes along the Autopista Las Americas in north central Puerto Rico – Implications for highway construction, design, and maintenance,* PhD dissertation, University Microfilms International, Ann Arbor, Michigan.

Moore, R., Dibb, T. M. and Billing, D. W. 1991. 'The distribution and causes of mass movements in Aurora Province, Philippines', in Bell, D. H. (Ed.), *Landslides, Proceedings of the Sixth International Symposium,* Christchurch, New Zealand, 1023–1029.

Pitts, J. 1992. 'Slope stability in Singapore', in Gupta, A. and Pitts, J. (Eds), *Physical Adjustments in a Changing Landscape, The Singapore Story,* Singapore University Press, Singapore, 259–300.

Reading, A. J., Thompson, R. D. and Millington, A. C. 1995. *Humid Tropical Environments,* Blackwell, Cambridge, MA, 429 pp.

Scatena, F. N. and Larsen, M. C. 1991. 'Physical aspects of Hurricane Hugo in Puerto Rico', *Biotropica,* **2**(4A), 317–323.

Schuster, R. L. 1978. 'Introduction', in Schuster, R. L. and Krizek, R. J. (Eds), *Landslides, Analysis and Control,* National Research Council, Transportation Research Board Special Report, **176**, 1–10.

Sidle, R. C., Pearce, A. J. and O'Loughlin, C. L. 1985. *Hillslope stability and land use,* American Geophysical Union Water Resources Monograph Series, **11**, 140 pp.

Sowers, G. F. 1971. 'Landslides in weathered volcanics in Puerto Rico', *Proceedings of 4th Panamerican Soil Mechanics and Foundation Engineering Conference*, **2**, 105–115.

Tan, B. K. 1984. 'Landslides and their remedial measures in Malaysia', *Proceedings of International Symposium on Landslides, 4th,* Toronto, **1**, 705–709.

US Department of Commerce, 1961. *Generalized estimates of probable maximum precipitation and rainfall-frequency data for Puerto Rico and the Virgin Islands,* Technical Report **52**.

Varnes, D. J. 1978. 'Slope movement types and processes', in Schuster, R. L. and Krizek, R. J. (Eds), *Landslides, Analysis and Control,* National Research Council, Transportation Research Board, Special Report **176**, 12–33.

Wagner, A., Leite, E. and Olivier, R. 1988. 'Rock and debris-slides risk mapping in Nepal – A user friendly PC system for risk mapping', in Bonnard, C. (Ed.), *Landslides, Proceedings of the Fifth International Symposium,* Lausanne, Switzerland, 1251–1258.

Wentworth, C. M., Ellen, S. D. and Mark, R. K. 1987. 'Improved analysis of regional engineering geology using geographic information systems', *Society of Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, Proceedings of 2nd Annual International Conference on GIS,* San Francisco, **2**, 639–649.

Wolfe, M. D. and Williams, J. W. 1986. 'Rates of landsliding as impacted by timber management activities in northwestern California', *Bulletin of the Association of Engineering Geologists*, **23**(1), 53–60.